

A new theory for light charged particle emission*

M Rajasekaran

Department of Nuclear Physics, University of Madras Guindy campus,
Madras-600 025, India

Abstract : We observe that deformation could significantly decrease the Coulomb barrier height and enhance charged particle emission in exotic decay of nuclei. Assuming the α -like clusters to move in an average field, the eigenvalues of the cluster bound state have been obtained using WKB approximation. These discrete levels should exhibit structure effects in the α -decay scheme. Are these observed or can they be observed? Results are presented for light nuclei like ^{26}Si and heavier ones $A \sim 220$.

Keywords : Charged particle emission, nuclear structure

PACS No. : 21.10 -k

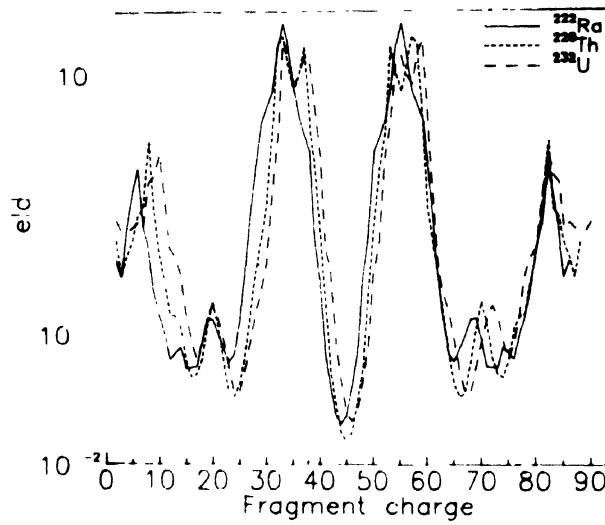
Recently Greiner and Sandulescu and their group [1–6] have made a comprehensive study of cold fission into super-asymmetric fragments which may also be considered as clusters. Their study is based on interesting experimental observations of Rose and Jones [7] of the University of Oxford and Ogloblin and Kurchatov [8] of the Institute of Atomic Energy in Moscow. Clusters like ^{14}C , ^{24}Ne , ^{58}Ni , apart from alpha particles, have been observed in a cold state, which implies that all the energy released has gone as kinetic energy of the fragments.

Charged particle emission from cold as well as hot nuclei, is a major source of information about nuclear structure. Charged clusters emitted carry a lot of information about their binding energy and shell structure of the parent and daughter nuclei. The separation energy of nucleons are greatly influenced by the deformation which at high spins, keep changing to restore stability in a relative sense. We have, in Ref. [9], already investigated the dependence of nuclear level density on spin, shape and excitation energy of the fused system and predicted enhanced emission of protons and neutrons at certain angular momentum states for a given excitation energy, due to single particle level crossings. Level crossing occurs due to deformation as well as nuclear rotation, especially

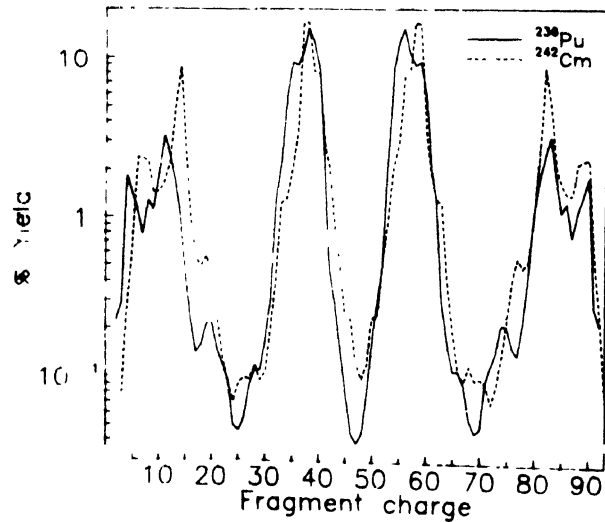
* Work supported by DAE through a research project

when high angular momenta are involved and spin alignment takes place along the axis of rotation. In Ref. [10], the separation energy of nucleons have been dealt with in an elaborate way. The value of the separation energy which is sensitive to deformation and spin of the nucleus decides the effective excitation in the residual nucleus. Hence the density of states for the products are influenced significantly by separation energy of the emitted particle.

The paper consists of two parts : a) determination of density of states for the products and b) quantum mechanical tunneling probability for light charged particle emission. Of the two parts, the first part will not be described here since the details of the calculation is well outlined by Tgnatyuk [12] and in our earlier work [13]. We present here only the results (Figures. 1 and 2) of the calculation to emphasise that light charged



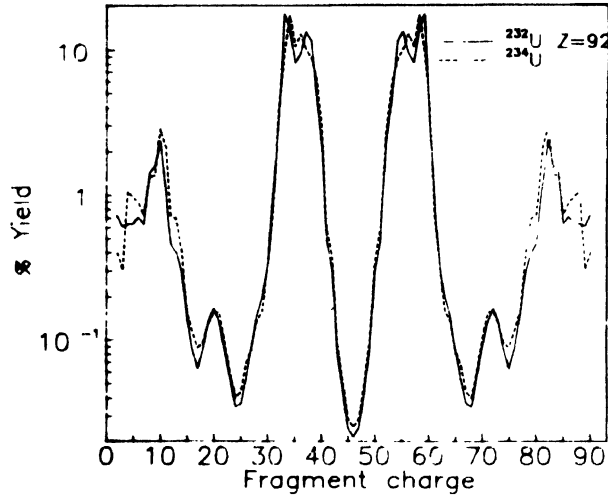
(a)



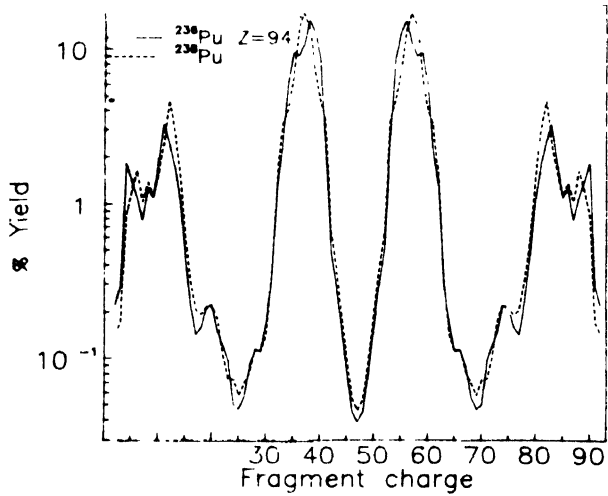
(b)

Figure 1(a). Yield vs the Fragment charges for the nuclei ^{222}Ra , ^{228}Th and ^{232}U . The excitation energy E^* is 60 MeV, (b) Same as Fig. 1(a) for ^{236}Pu and ^{242}Cm .

particles ranging from ^{14}C to ^{58}Ni do indeed have significant probability in the charge distribution even at high excitation.



(a)



(b)

Figure 2(a). Same as Fig. 1(a) for ^{232}U and ^{234}U . (b) Same as Fig. 1(a) for ^{236}Pu and ^{238}Pu

In the present note, I am going to deal with the state of the cluster inside the parent nucleus as a composite system where it should move in an average field of the A-A cluster nucleons. The average field is a combination of the effective nuclear field and the Coulomb field. We have used a Woods-Saxon type potential with a suitable depth which makes the cluster to float above the well depth but still bound by the positive barrier above the nuclear potential. The radius of the orbits of these clusters are usually larger than the radius of the daughter nucleus. We have used the WKB method to obtain the bound state energies and

the penetration coefficient. The eigen energies are positive or negative depending on the Q value of the reaction in which the cluster is emitted in a cold state and leaks out by tunneling. The kinetic energy of the cluster at infinity which is equal to the Q value appears as the energy of the cluster in the bound state, for *eg.*, in the reaction $^{223}\text{Ra} \rightarrow ^{209}\text{Pb} + ^{14}\text{C}$, the Q value is 31.85 MeV and the barrier height is ~ 70 MeV. The depth of the Woods-Saxon potential is adjusted to yield an eigen value of 31.85 MeV which is approximately 40 MeV below the barrier. The tunneling probability is then determined for this energy of the cluster. This way, we have treated the motion of the cluster inside and outside in a consistent manner. One can also use a numerical code to evaluate the eigen value and eigen function and determine the emission probability by calculating the amplitude at the entrance and exit points of the barrier

This mechanism is different from that envisaged by Greiner's group where they use the TCSM in which valence nucleons of the cluster and daughter nuclei are shared and highly elongated shapes evolve before they separate. In the present theory, the cluster exists as a group of nucleons in correlated motion relative to the center of mass of the daughter.

The eigen value E is determined using the WKB expression

$$\int_{r_1}^{r_2} K(r) dr = \left(n + \frac{1}{2} \right) \pi$$

where $K(r) = \left[2M_c(E - V(r)/\hbar^2) \right]^{\frac{1}{2}}$

with $V(r) = V_0 / \{1 + \exp[(r - R)/d]\} + V_{\text{Coul}} + \left(l + \frac{1}{2} \right) / 2\mu r^2$

The Coulomb potential V_{Coul} is of the usual type - parabolic inside and inversely proportional to r outside.

The potential parameters for spherical nuclei and the Q values for various reactions in which light clusters are emitted, are listed in Table 1.

Table 1. Q Values, calculated and experimental half lives T and potential depth V_0 corresponding to the eigenvalue of the cluster which is equal to the Q value, for different emitted and daughter nuclei combinations. These values are for $l = 0$ and diffuseness $d = 0.5$ fm

						$l = 0,$		$d = 0.5$	
Emitted		Daughter		Q	$r_0 = 1.1^*$		$r_0 = 1.05^*$		log T (sec) Expt
A_c	Z_c	A_d	Z_d		V_0 calc	log T	V_0 calc	log T	
14	6	208	82	33.05	61.59	9.683	66.69	11.615	11.02 \pm .06
14	6	209	82	31.85	62.75	11.848	67.85	13.806	15.20 \pm .05
14	6	210	82	30.53	64.03	14.392	69.13	16.377	15.90 \pm .12
14	6	212	82	28.21	66.34	19.369	71.34	21.389	21.33 \pm .20
20	8	208	82	44.72	75.39	17.804	81.87	20.424	20.86 \pm .30
24	10	208	82	62.40	83.36	14.869	91.26	17.948	21.06 \pm .10

Table 1. (Cont'd.)

Emitted		Daughter		Q	$r_0 = 1.1^*$		$r_0 = 1.05^*$		log T (sec. Expt
A_e	Z_e	A_d	Z_d		V_0 calc	log T	V_0 calc	log T	
24	10	210	82	58.84	86.84	19.960	94.71	23.123	$25.25 \pm .05$
28	12	206	80	74.13	93.10	18.046	102.16	21.591	$25.75 \pm .06$
28	12	208	82	79.46	91.20	14.013	100.47	17.523	$21.68 \pm .15$
28	12	210	82	75.73	94.83	18.584	104.08	22.184	$25.70 \pm .25$
34	14	208	82	96.42	96.43	13.998	107.36	18.028	23.24

* The reduced radius parameter r_0 is not constant and decreases with increasing mass number and has a discontinuity at $N = 126$. [Ref. Buck *et al. Phys. Rev. Lett.* **65** 2975 (1990)]

The eigen values for the systems ${}^4\text{He} + {}^{24}\text{Mg}$ and ${}^{14}\text{C} + {}^{209}\text{Pb}$ are given in Table 2, for different orbital and radial quantum numbers. The first system is interesting since the

Table 2 Eigenvalues of excited states of clusters for different orbital (l) and radial (n) quantum numbers

Emitted		Daughter		d = 0.5 fm			= 1.2 fm	
A _e	Z _e	A _d		V _{barrier} (MeV)	V ₀ (MeV)	n	l	E (MeV)
		24	12	7.02996	21.10938	0	0	-9.98189
						0	1	-8.00063
						0	2	-5.42161
						0	3	-2.35626
						0	4	1.08703
						0	5	4.80331
						0	6	8.64771
						1	0	-4.42391
						1	1	-0.86425
						1	2	2.68385
14		209	82	70.79525	60.49072	0	0	31.85122
						0	5	32.54465
						0	10	34.60325
						0	15	37.96667
						0	20	42.56066
						0	25	48.31008
						0	30	55.14586
						1	0	36.91339
						1	5	37.72711
						1	10	40.10360
						1	15	43.90134
						1	20	48.97454
						1	25	55.19708
						1	30	62.46172

Table 2. (Cont'd)

Table 2. (Cont'd)				d = 0.5 fm	f ₀	= 1.2 fm	
Emitted		Daughter		V ₀ (MeV)	n	l	E (MeV)
A _e	Z _e	A _d	Z _d				
					2	0	41.19325
					2	5	42.17668
					2	10	44.96471
					2	15	49.26451
					2	20	54.83694
					2	25	61.50134
					2	30	69.10101

study of Eswaran *et al.* [14] has indicated a resonance structure with possible collective rotation like decay scheme *i.e.*, $l(l+1)/\mu < r^2 >$, with large moment of inertia.

In Figures 1 and 2, we show the charge distribution in binary fission of Ra, Th, U, Pu and Cm isotopes. The emphasis here is on light charge particles (LCP) like C, O, Mg, Ne, S, Si etc. The probability of emission of these LCPs is summed over all isotopes of the element and are pronounced and the only hinderance factor would be barrier penetration coefficient.

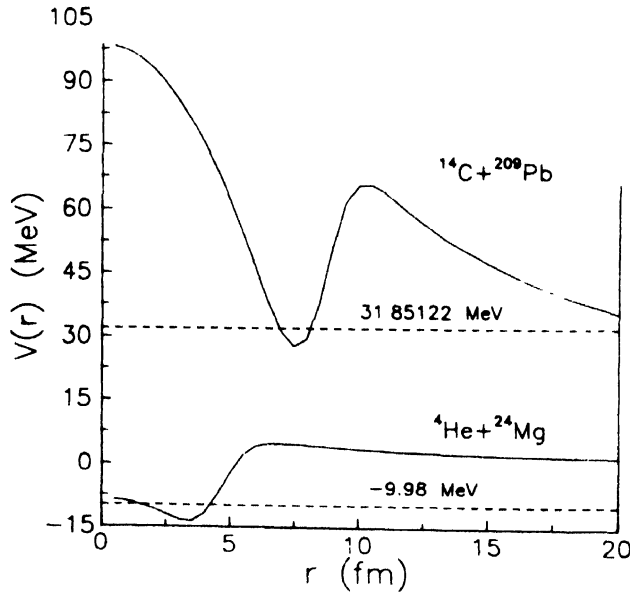


Figure 3. The effective potential for the systems ${}^4\text{He} + {}^{24}\text{Mg}$ and ${}^{14}\text{C} + {}^{209}\text{Pb}$. The eigen values are indicated by horizontal lines.

In Figure 3 the effective potential and eigenvalues of clusters are shown for ${}^4\text{He} + {}^{24}\text{Mg} \rightarrow {}^{28}\text{Si}$ and ${}^{14}\text{C} + {}^{209}\text{Pb} \rightarrow {}^{223}\text{Ra}$.

It should be worthwhile to investigate the spectroscopy of the emitted charged particles experimentally as is obvious from the results of the present calculation. The threshold excitation function can be had from Table 2.

I conclude by stating that a semi-classical treatment for cluster dynamics while in the composite state and subsequent emission of light charged particles has been developed. From a knowledge of the phase space and transmission coefficient for the LCP, it is predicted that the emitted particle may give information about the structure in the composite state.

10

References

- [1] A Sandulescu and W Greiner *Rep. Prog. Phys.* **33** 1423 (1992)
- [2] A Sandulescu, H J Lustig, J Hahn and W Greiner *J. Phys. G : Nucl. Phys.* **4** 1279 (1978)
- [3] A Sandulescu, D N Poenaru and W Greiner *Sov. J. Part. Nucl.* **11** 528 (1980)
- [4] W Greiner *et al. Treatise on Heavy Ion Physics, Nuclei Far from Stability* vol. 8 ed. D A Bromley (New York : Plenum) p 641
- [5] P B Price *Nucl. Phys.* **A502** 41c (1989)
- [6] A Sandulescu *J. Phys. G : Nucl. Part. Phys.* **15** 529 (1989)
- [7] H J Rose and G A Jones *Nature* **307** 245 (1984)
- [8] W Kutschera *et al. Phys. Rev.* **C32** 2036 (1985)
- [9] M Rajasekaran, T R Rajasekaran and N Arunachalam *Phys. Rev. ibid* **38** 307 (1988)
- [10] M Rajasekaran, T R Rajasekaran, N Arunachalam and V Devanathan *ibid* **38** 1926 (1988)
- [11] M Rajasekaran, T R Rajasekaran, N Arunachalam and V Devanathan *Phys. Rev. Lett.* **61** 2077 (1988)
- [12] A V Ignatyuk *Phys. Lett.* **76B** 543 (1979)
- [13] M Rajasekaran and V Devanathan *Phys. Rev. C* (1982)
- [14] M A Eswaran *et al. Phys. Rev.* **C47** 1418 (1993)